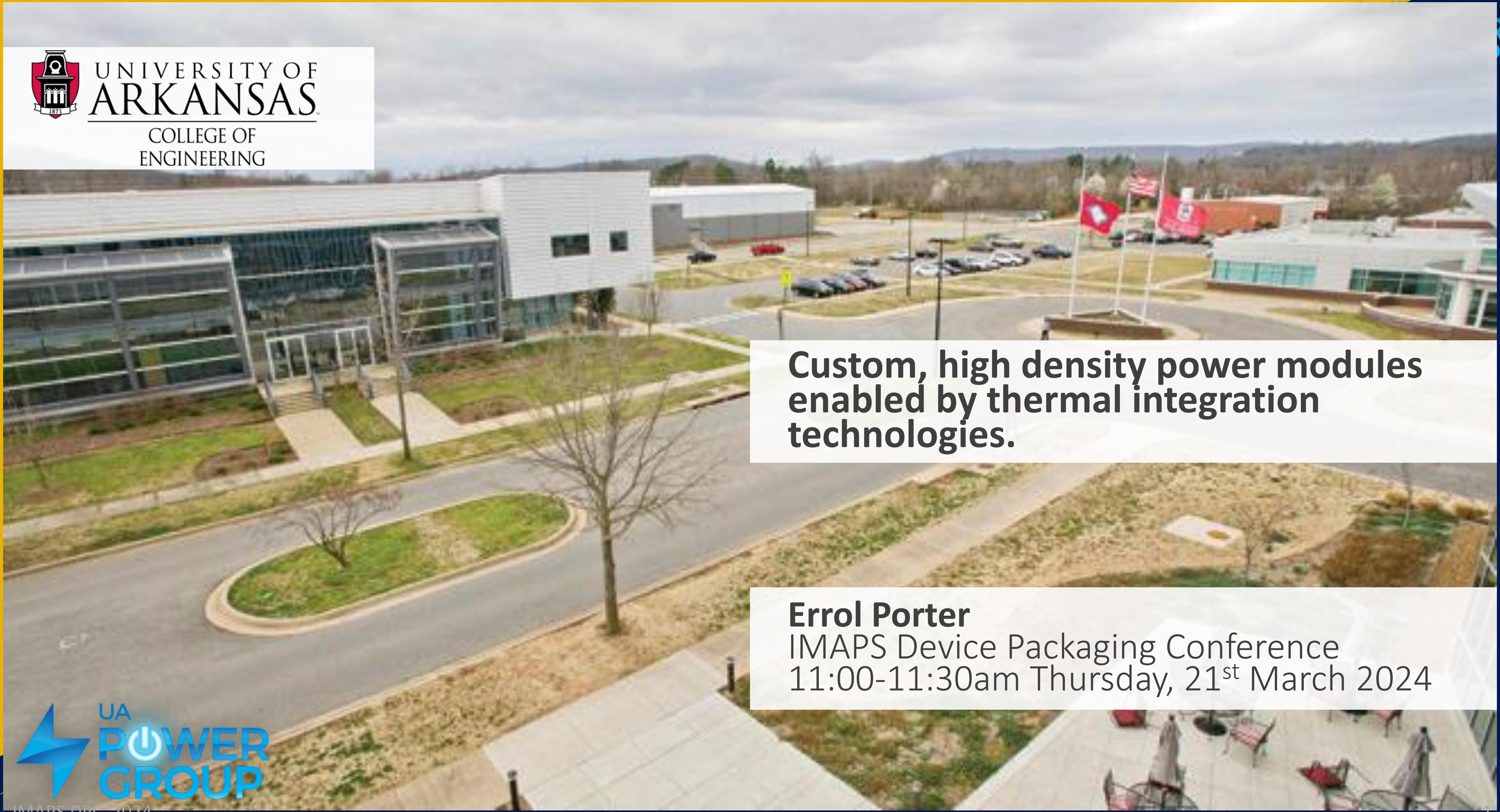
UNIVERSITY OF ARKANSAS
COLLEGE OF ENGINEERING



Custom, high density power modules enabled by thermal integration technologies.

Errol Porter
IMAPS Device Packaging Conference
11:00-11:30am Thursday, 21st March 2024

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About us

The University of Arkansas Power Group

- Committed to advancing the frontiers of knowledge and innovation in the foundational technologies and applications of power electronics from materials through systems.

DEVICE — MUSiC MULTI-USER SILICON CARBIDE National Semiconductor Research and Fabrication Facility — Only low-volume SiC integrated circuit fabrication facility.

MODULE — HiDEC University of Arkansas • High Density Electronics Center — Most comprehensive low-volume module fabrication facility.

SYSTEM — NCREPT National Center for Reliable Electric Power Transmission — Unique system and medium voltage test facility.

Multi-User Silicon Carbide (MuSiC) – R&D Facility

Nikon NSR2005i8A i-line stepper is a sub-micron pattern transfer tool capable of 0.5-micron resolution. Tool handling has been modified to register the pickup transparent SiC wafers during loading and unloading procedures.

MuSiC R&D Division

The National Multi-User Silicon Carbide Research Fab (MUSiC), is the only low-volume SiC integrated circuit fabrication facility, as a national resource open for your use, prototyping and proof-of-principle demonstrations of novel ideas, all of which provide the opportunity for American researchers to develop new and novel breakthroughs in the semiconductor area.

LAM 590 Plasma etcher
An in-line cassette to cassette, single wafer parallel plate plasma etching system normally used for etching silicon oxide and or nitride.

SiC Device Processing Tools:

Nikon NSR 2005 I8a stepper
Centrotherm c.Activator 150-50
Centrotherm Oxidator
LPE's PE106 SiC epitaxial reactor
LAM490 & 590 plasma etcher

Centrotherm c.Activator 150-50
The tool's main application is the electrical activation by post implantation annealing of SiC devices on 150mm wafers at temperatures up to 2000ºC.

High Density Electronics Center (HiDEC) - LTCC

Microtec 550TVC
Thick film screen printer for 200 mm square GreenTape. System utilizes a desktop PC with image capture software to help with screen to tape alignment.

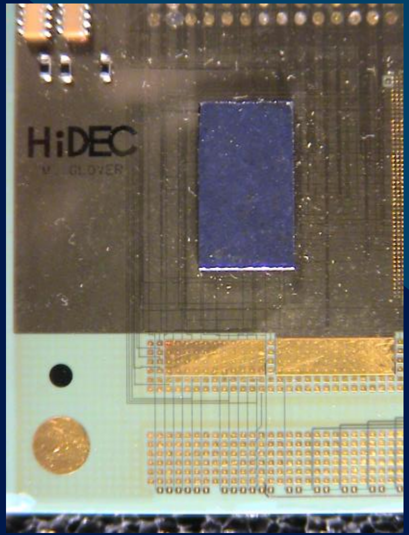
HiDEC Ceramics Division

The ceramics integration laboratory houses punch, print, in-situ metrology, collate, laminate and firing tooling. The facility also holds wet etch, dry etch and dicing capabilities. This segment of the core facility aims to provide services of thick film circuitry for high frequency and extreme environment applications at both an R&D as well as pilot production volume.

Avure Technologies IL142005_SS
A batch-mode, semi-automatic isostatic lamination tool is currently configured to handle a batch of GreenTape assemblies hand packaged in water-tight and vacuum-sealed bags.

Thick Film Processing Tools:

UHT 8200Z SL punch
Baccini punch
Microtec 550TVC screenprinter
Stratus III Automated optical inspection tool
Baccini collator
Avure Technologies IL142005_SS laminator
Thermo Scientific 55.3L furnace
SierraTherm LTCC furnace



Northrop Grumman 3D stacked demonstration module. A thin-film on LTCC proof of concept deliverable demonstrating 0.5mm pitch, dematable z-axis electrical connections using spray cooling and diamond heat spreaders for thermal management.

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High Density Electronics Center (HiDEC) - Assembly

SST 5100
The programmable vacuum furnace is routinely used to obtain void-free solder joints without the use of flux. This unit has a formic acid preclean cycle run at 210°C and a reflow heat limit of 450°C in an inert gas (4% hydrogen in nitrogen) from vacuum levels at 50mTorr to pressures exceeding 40 psig. Parts are heated on a graphite plate with up to four temperature probes that can be placed at different sites.

HiDEC Module Assembly Division

The module integration laboratory houses the most common equipment necessary to complete the final stages of the electronic packaging processes including wire bonding, soldering, and flip-chip attachment.

Exact Dispensing VC-18 Vacuum chamber designed to create a vacuum environment while dispensing encapsulant to insure void free coverage.

Assembly Processing Tools:

Diener PICO 5 asher
Exact Dispensing VC-18 encapsulation chamber
Finetech Sigma 2406 die bonder
Hesse BJ935 heavy {copper} wire bonder
K&S 4523 wire bonder
Sikama Falcon 5/C solder reflow oven
SST 3130HT vacuum brazing furnace
SST 5100 vacuum reflow oven
Valhalla 5880A hi-Pot tester

Hesse BJ935 The Bond Jet BJ935 is an ultrasonic wedge-wedge wire bonder developed for fully automated or manual processing of a wide range of substrates, chips, and other materials. Though currently configured for 12mil aluminum wire, the tool has accessories to allow for ribbon and even copper bonding..

HiDEC
University of Arkansas • High Density Electronics Center

National Center for Reliable Electric Power Transmission (NCREPT) – Medium Voltage Testbed

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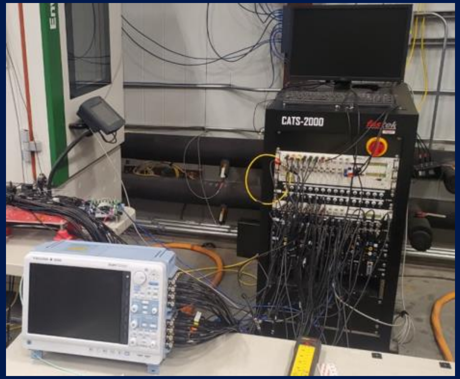
Simplex Electra 700KW Digital Load Bank This very large capacity, high performance portable load bank is designed to provide users of large AC generators and UPS systems with sophisticated testing capability. The bank features digital controllers with network control and data acquisition capability. All electrical values display on the screen and are recorded by the system for future data retrieval.

NCREPT Medium Voltage Test Division

Established in 2005, NCREPT was established for the purpose of investigating solid-state solutions for high voltage applications such as the electric power grid including both protection devices as well as energy storage.



FasTek CATS 2000 NI-Based Data Acquisition Unit is This CATS-2000 specification is targeted toward a unit developed specifically for power distribution system analysis and certification. The unit is built within an EMI shielded 19" rack enclosure with a shielded input system as it was designed to be placed in a highly "noisy" electronic environment, and system operation was intended to be controlled and viewed remotely via a 500' fiber optic link.

Medium Voltage Testing Equipment:

750 kVA Variable-Voltage Variable-Frequency Drive (VVVF)

2 MVA Regenerative Electronic Loads (REGEN)

2.5 MVA 3ϕ Resistive Load Bank

600 V/750 kW DC Power Supply

700 kW 3ϕ Resistive Load Bank

120-ton Chiller Unit and Heat Exchanger

FasTek CATS 2000 NI-Based Data Acquisition Unit

Various Instrumentation and Equipment to Support Research and Testing

Baldor Vector Drive This 750 kVA Variable-Voltage Variable-Frequency Drive (VVVF) is used for medium voltage operation.

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Abstract Breakdown

What to expect from this presentation

The compilation of topics presented directly target enhancing power module electrical and thermal performance capabilities.

Topics include:

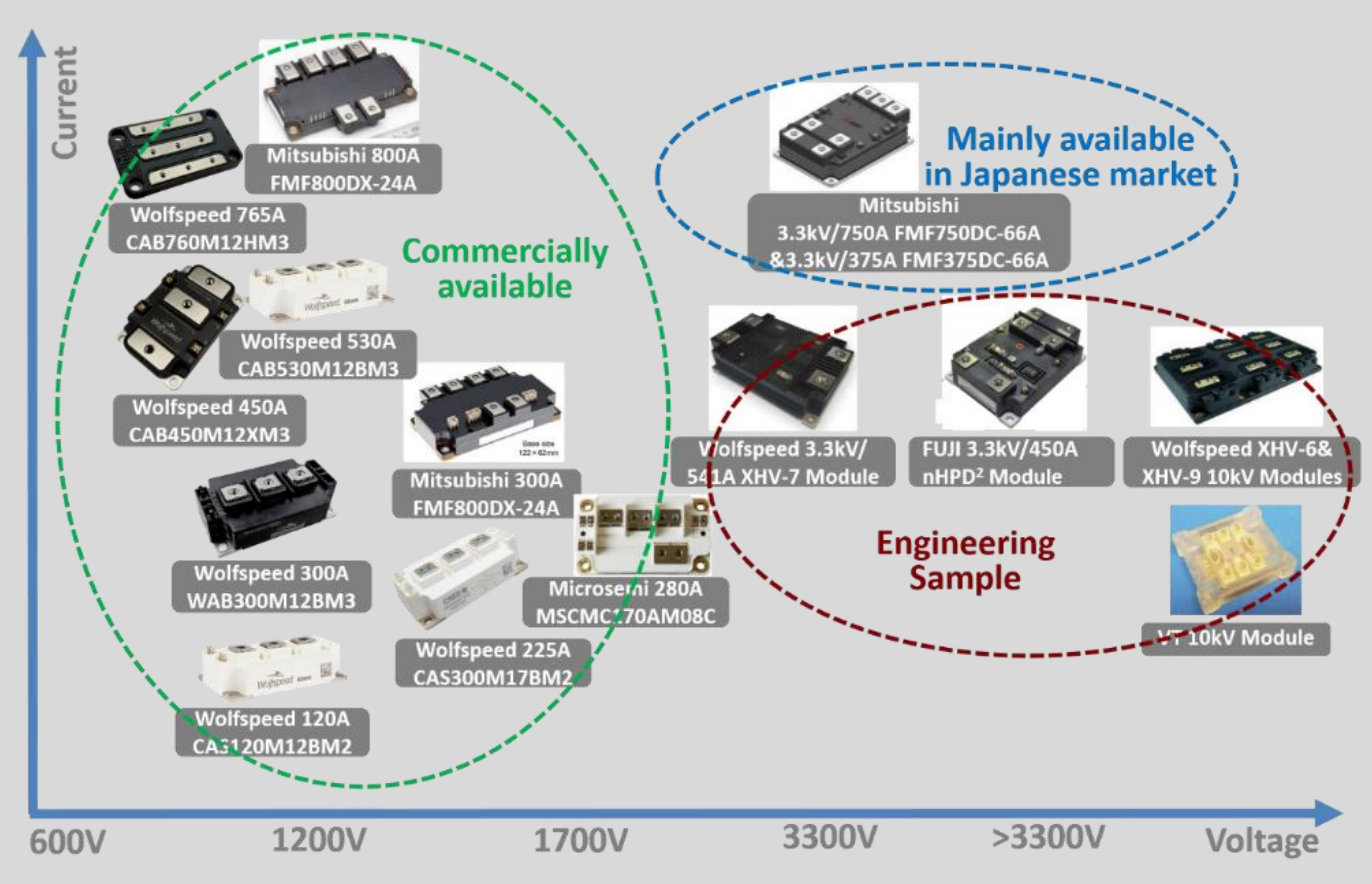
1. A look at UAPG's advancements in custom power module design, fabrication and evaluation
2. A discussion of the critical role of thermal management in enhancing the efficiency and reliability of high-voltage power modules,
3. Present a few case studies to showcases a variety of innovative solutions.
   a. Case study 1: 1.7 kV, 1600 A module in a ~100 cm^3 form factor.
   b. Case study 2: 3.3 kV, 200 A module in a ~250 cm^3 form factor.
   c. Case study 3: 10 kV, 60 A module in a ~420 cm^3 form factor.

Commercial Module Availability

≤ 1.7kV and below are commercially available

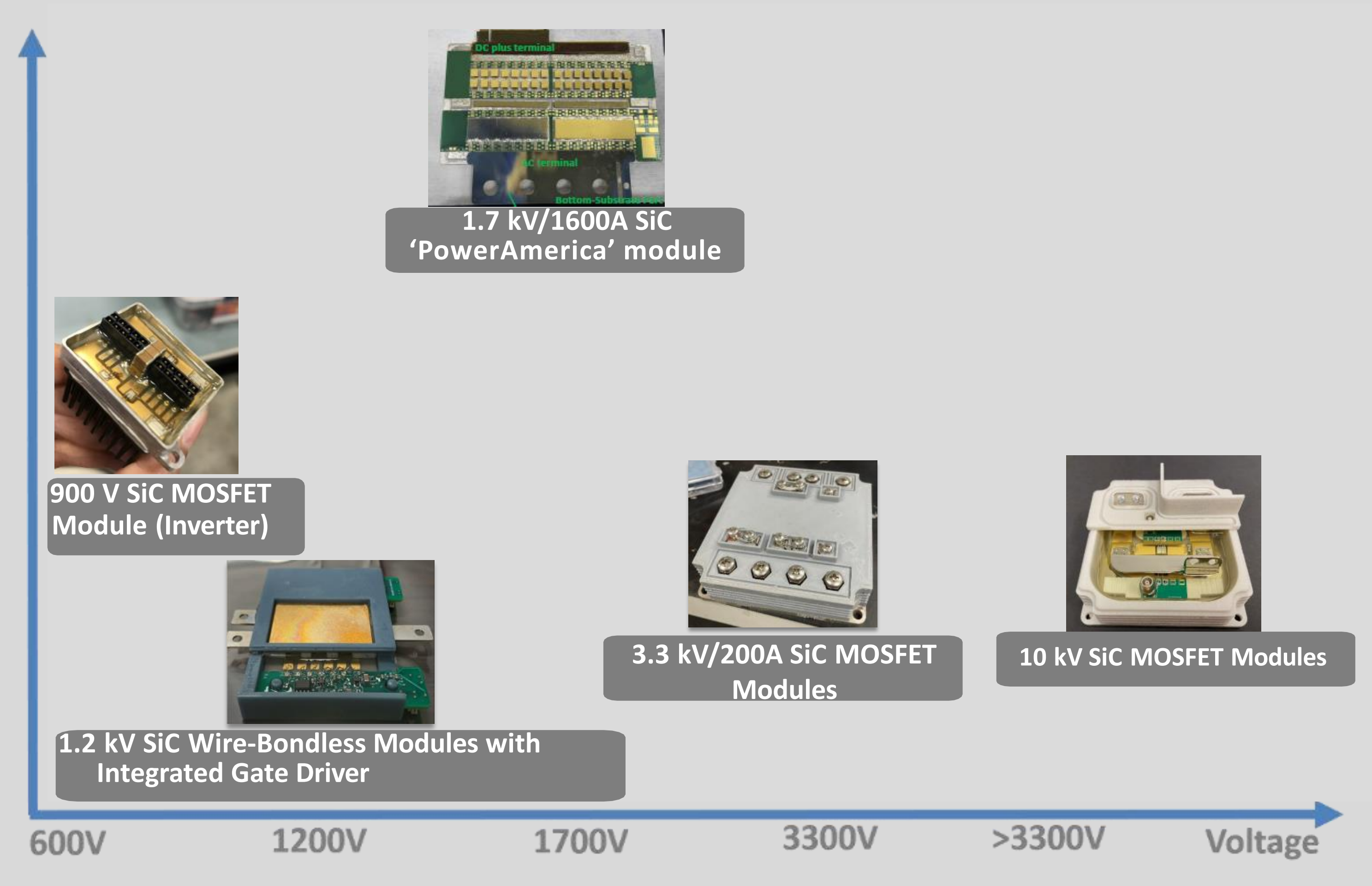
≥ 3.3kV modules remain experimental

Leaves room for research and development



UAPG Power Module Development Overview

Showcase of UAPG contribution to the development of power modules across the high-voltage spectrum to address the needs of electric vehicles and related high-power applications.

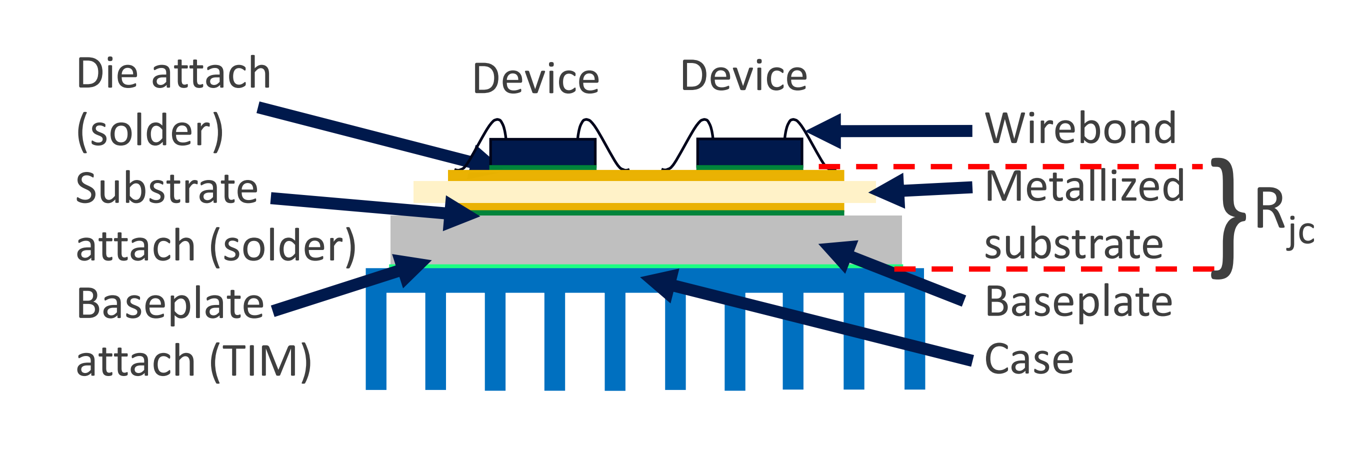


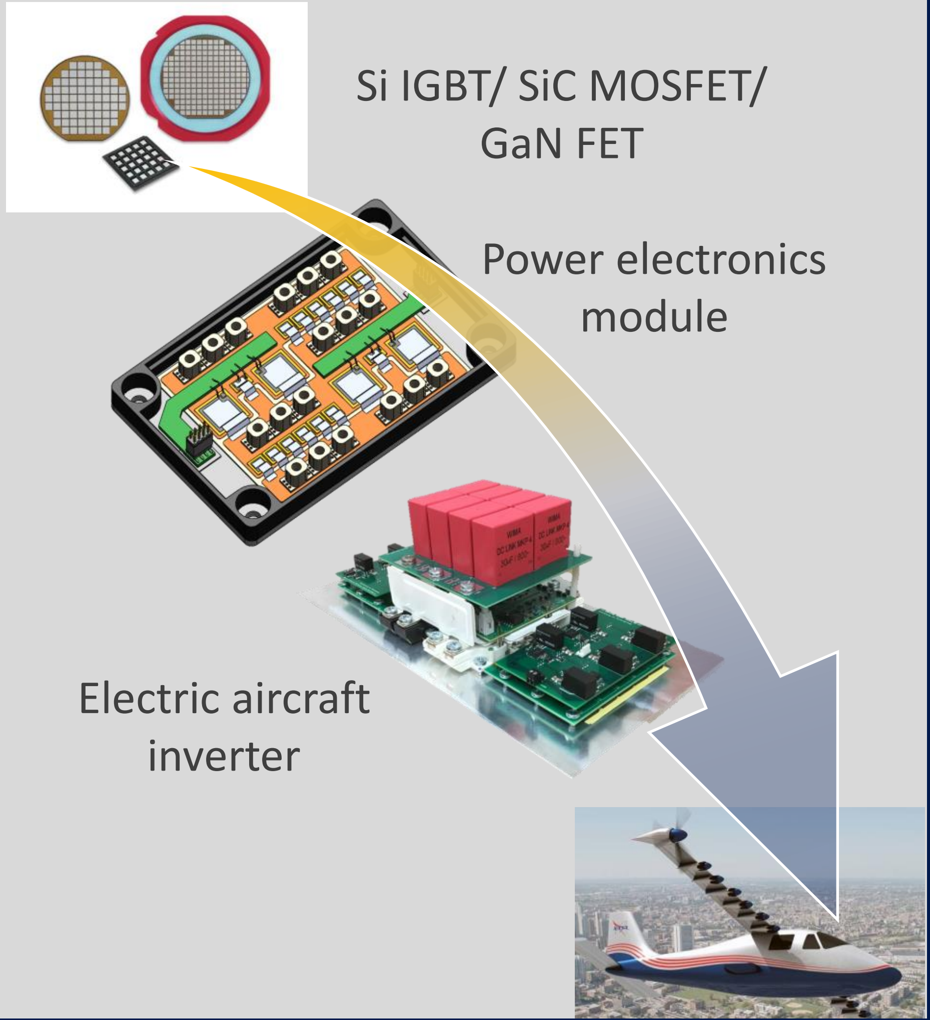
Conventional Cooling Solution

Power electronics an integral part of electrified systems

- Enable power conversion and control

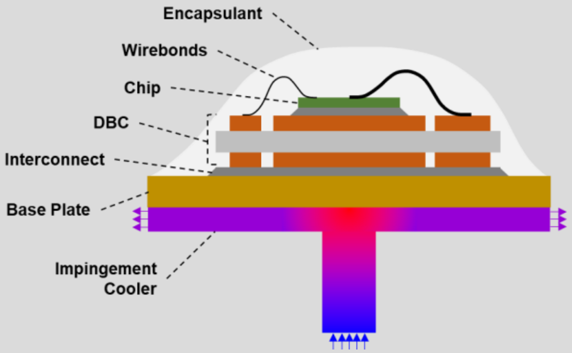
- Modules dissipate heat due to:
  - Switching and conduction losses
- Cooling achieved through external-to-case solutions which we will term a level 0 integration.





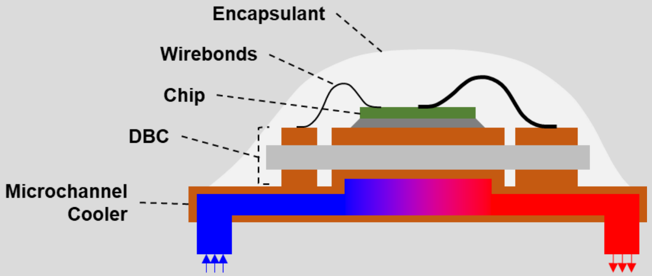
Thermal Cooling vs. Thermal Resistance

R''_{th}



- Removal of TIM* layer
- Direct base plate cooling
- Medium thermal spreading reduction

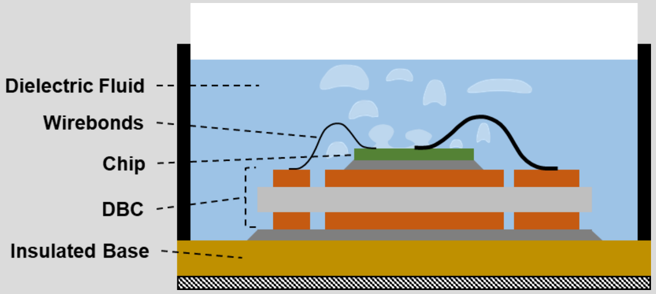
- Cooling imbedded in DBC
- Increased manufacturing complexity
- Thermal gradients in microchannels, but not present in impingement methods



Level 3 Reliability Effects

- Removal of CTE mismatch between layers
- Additional cooling on wirebonds
- No cracked encapsulation

- Chip in direct contact with coolant
- Material compatibility concerns
- Forced convection to avoid boiling



Improved Reliability

*TIM – Thermal Interface Material commonly applied between baseplate and conventional heatsink.

Level 1 Integration | Level 2 | Level 3

Advanced Cooling Solutions

- State of the art power module cooling strategies
- Microchannel and jet impingement to be discussed

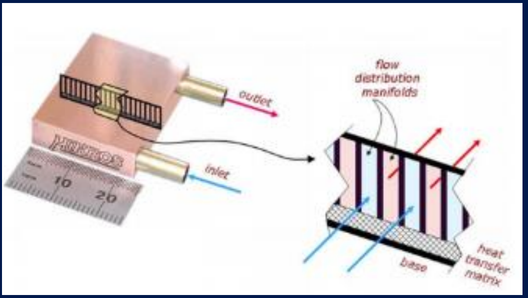


Fig. 7: Microchannel cooling [3]

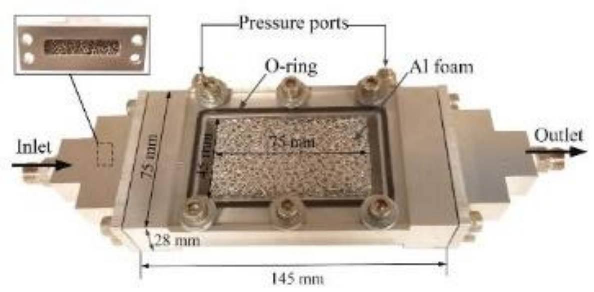


Fig. 8: Microporous cooling [4]

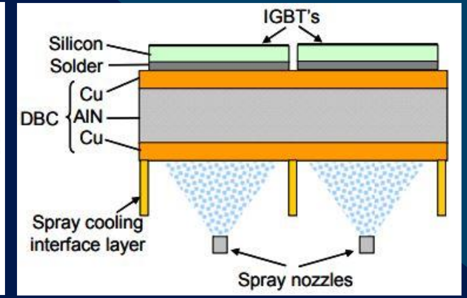


Fig. 9: Spray cooling [5]

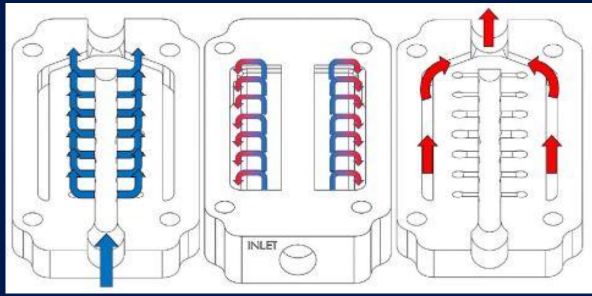


Fig.10: Jet Impingement cooling [6]

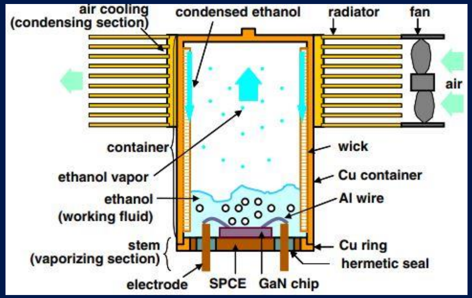


Fig.11: Pool boiling [7]

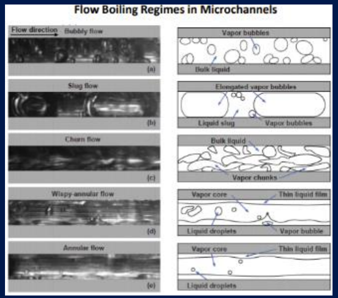


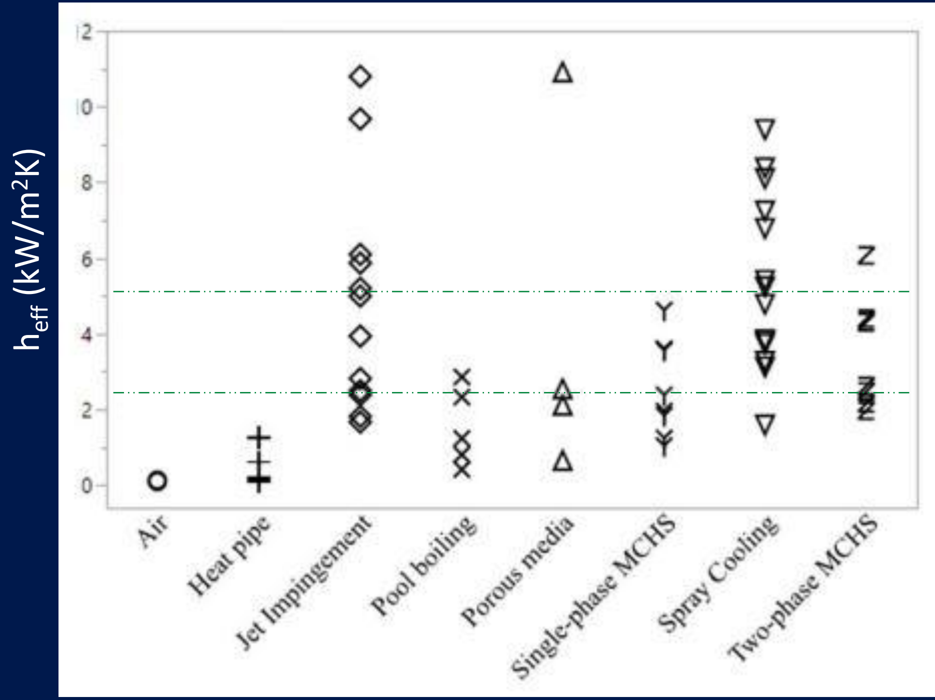
Fig.12 Flow boiling [8]

[3] https://www.microcoolingconcepts.com/
[4] Y. Li, L. Gong, B. Ding, M. Xu, and Y. Joshi, “Thermal management of power electronics with liquid cooled metal foam heat sink,” Int. J. Therm. Sci., vol. 163, p. 106796, May 2021, doi:10.1016/j.ijthermalsci.2020.106796.
[5]H. Bostanci, D. Van Ee, B. A. Saarloos, D. P. Rini, and L. C. Chow, “Spray cooling of power electronics using high temperature coolant and enhanced surface,” in 2009 IEEE Vehicle Power and Propulsion Conference, Sep. 2009, pp. 609–613. doi: 10.1109/VPPC.2009.5289793
[6] R. Whitt, D. Huitink, A. Emon, A. Deshpande, and F. Luo, “Thermal and Electrical Performance in High-Voltage Power Modules With Nonmetallic Additively Manufactured Impingement Coolers,”IEEE Trans. Power Electron., vol. 36, no. 3, pp. 3192–3199, Mar. 2021, doi:10.1109/TPEL.2020.3015226.
[7] [5]H. N. Otsuka, S. Nagai, M. Yanagihara, Y. Uemoto, and D. Ueda, “Low pressure direct-liquid-cooling technology for GaN power transistors,”Jpn. J. Appl. Phys., vol. 50, no. 4S, 2011, Art. no. 04DF07.
[8] Justin A. Weibel, Thermal Management of Electronics https://nanohub.org/resources/27678/download/2017.11.20-CNIT581-Weibel.pdf

Cooling Comparisons

Performance comparison of emerging thermal management solutions.

- Many capable ≥ 2.5 kW/m^{2}K
- Few options ≥ 5 kW/m^{2}K



Effective heat transfer coefficient, h_{eff}:

$$h_{\text{eff}} = \frac{Q}{A_{\text{hs}}(T_d - T_i)}$$

Where T_d is the device temperature, T_i is the coolant inlet temperature or saturation temperature, Q is the heat dissipation rate, and A_{hs} is the heat sink base area or the cooled surface area

MCHS: Microchannel heat sink

[9] A. Iradukunda, D. R. Huitink and F. Luo, "A Review of Advanced Thermal Management Solutions and the Implications for Integration in High-Voltage Packages," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 1, pp. 256-271, March 2020,

Integrated Cooling Case Study

1.7kV, 1600A power module

1.7 kV PowerAmerica Challenge Module [1]

- UAPG develop 1.7 kV, 1600A (SiC) half-bridge power module with
  - Compact formfactor (98.8 cm^3)
  - Double-side cooling architecture
  - Integrated capacitors and gate resistors

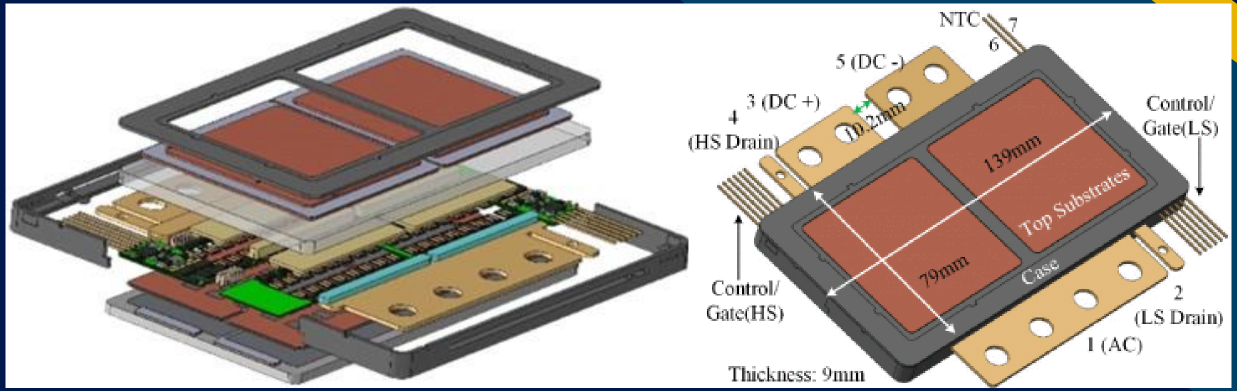


Fig. 1: Module Architecture.

Package Characteristics	Value
Dimensions	139 x 79 x 9 mm
Module inductance (Q3D estimation)	0.92nH
Integrated gate resistance	1.25 Ω

Fig. 2: Module internal layout

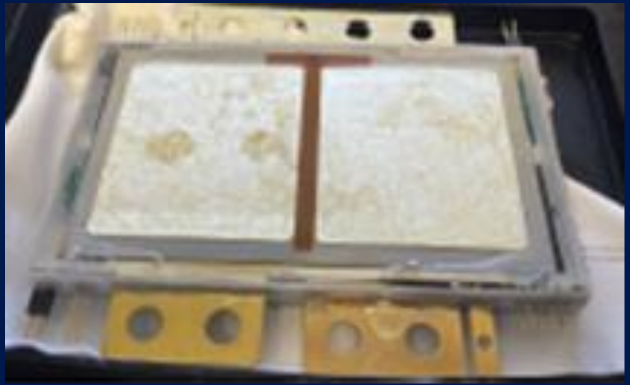


Fig. 3: Module appearance

[1] Y. Chen, A. Iradukunda, H. A. Mantooth, Z. Chen and D. Huitink, "A Tutorial on High-Density Power Module Packaging," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 11, no. 3, pp. 2469-2486, June 2023

1.7 kV PowerAmerica Challenge Module

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- PowerAmerica module provided a good platform to evaluate various cooling methodology
  - Complete module utilizes 64 die
  - Total power loss estimated at 5,952 W
  - Traditional cooling proves problematic at a $100cm^3$ formfactor

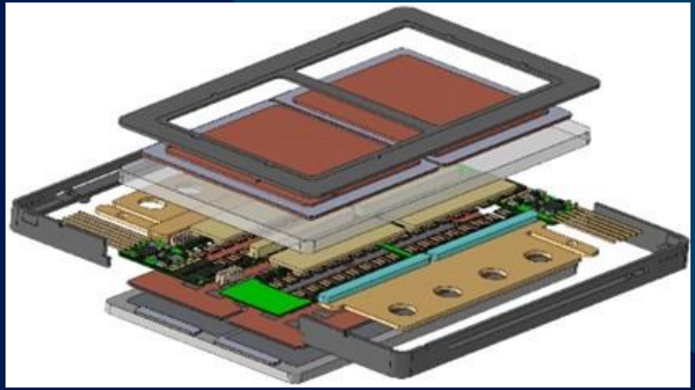


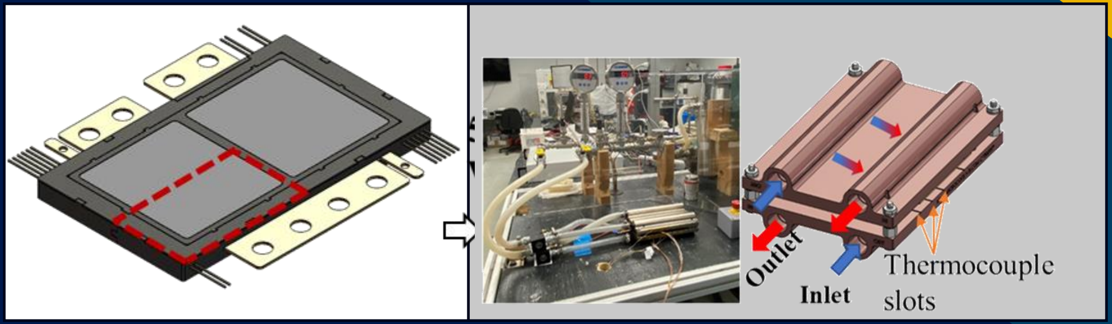
Fig. 1: Module Architecture.

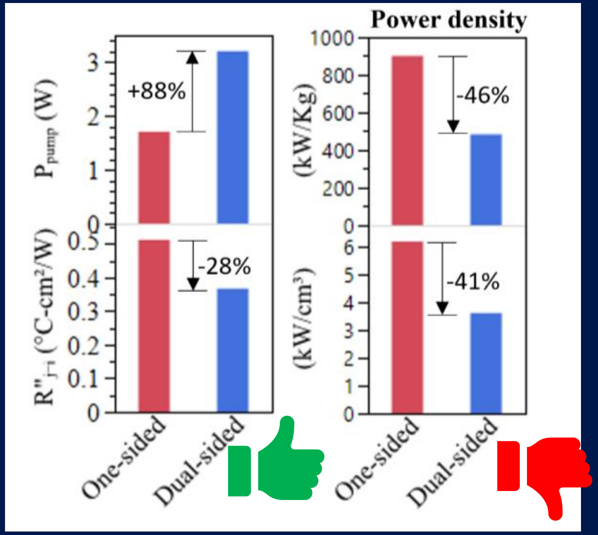
Package Characteristics	Value
Conduction loss of MOSFET P_cond	60W (For Rds(on)(175 °C) : 78.75 mΩ)
Switching losses of MOSFET P_swM	31W
Turn-on loss of MOSFET caused by reverse-recovery of the free-wheeling diode P_swD	1.4625W
Total losses per MOSFET	93W

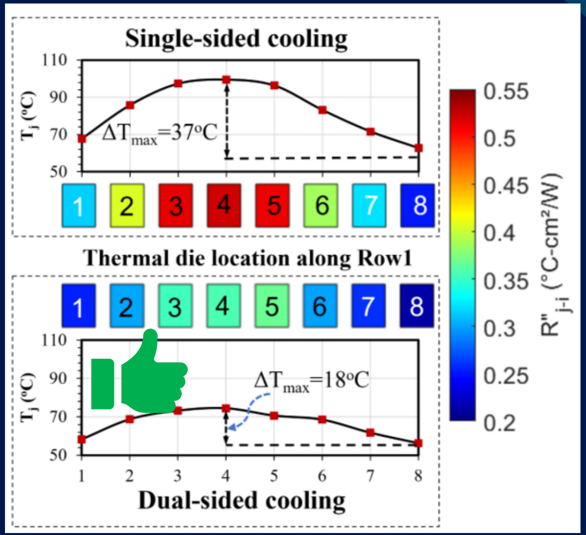
[12]: A. -C. Iradukunda et al., "Toward Direct Cooling In High Voltage Power Electronics: Dielectric Fluid Microchannel Embedded Source Bussing Terminal," in IEEE Transactions on Components, Packaging and Manufacturing Technology, doi: 10.1109/TCPMT.2024.3369554.

1.7 kV Module – External Single vs Double Sided

- Designed external cooler on a portion of module for evaluation purposes.
- Case cooler tested and evaluated with only one then both sides operating.
- Dual-sided cooling does reduce thermal resistance
- Also provides significant cooling uniformity across the thermal die
- But the added pumping power would impact the overall power density.





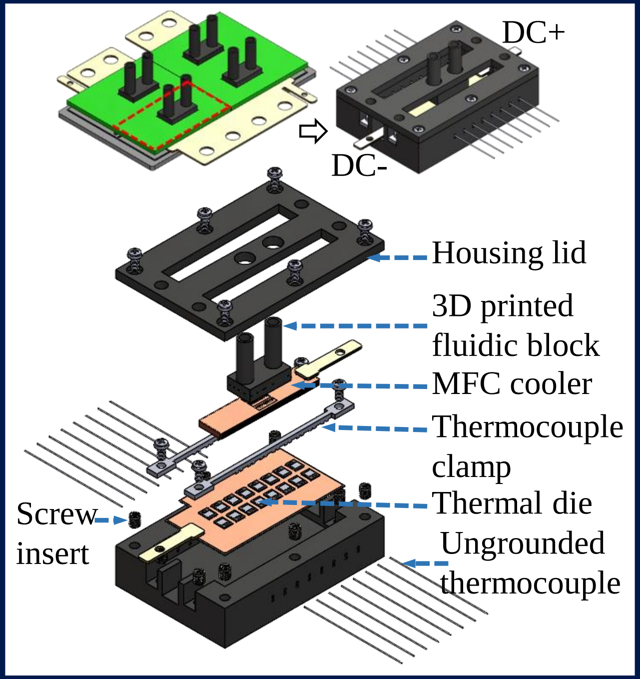


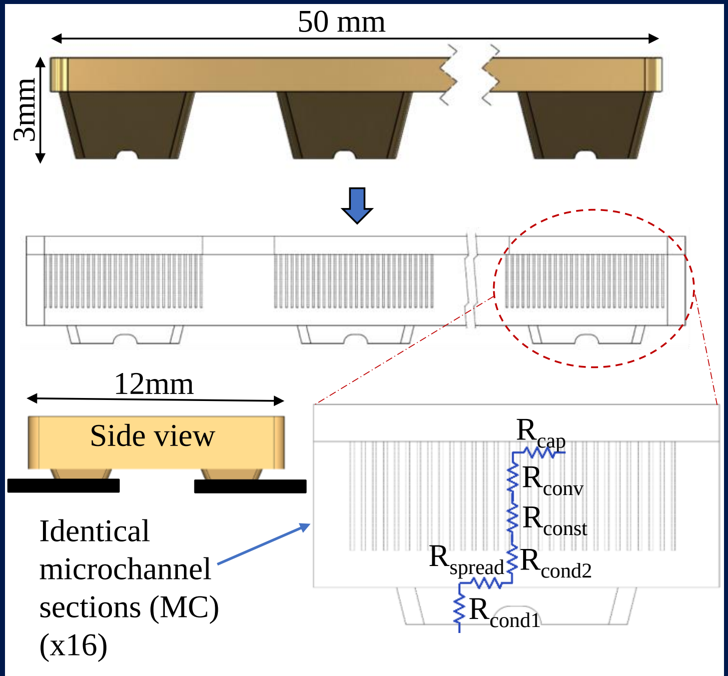
[12]: A. -C. Iradukunda et al., "Toward Direct Cooling In High Voltage Power Electronics: Dielectric Fluid Microchannel Embedded Source Bussing Terminal," in IEEE Transactions on Components, Packaging and Manufacturing Technology, doi: 10.1109/TCPMT.2024.3369554.

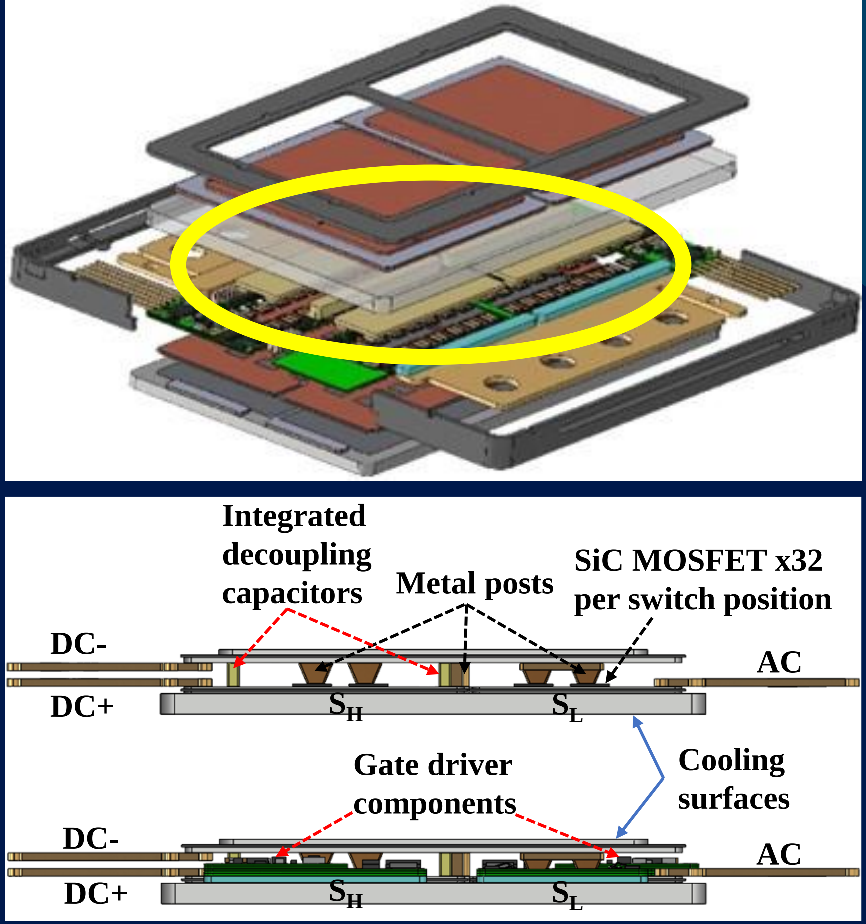
Microchannel Modification details

- UAPG modified the 1.7 kV, 1600A (SiC) design with microchannel integrated cooling
  - Die to terminal machined conductor replaced with a microchannel version.*
  - Dielectric fluid to flow through microchannels.
  - Revised Mutli-Function Cooler (MFC) provides a dual purpose.

* Realized through Micro Cooling Concepts, Inc. partnership



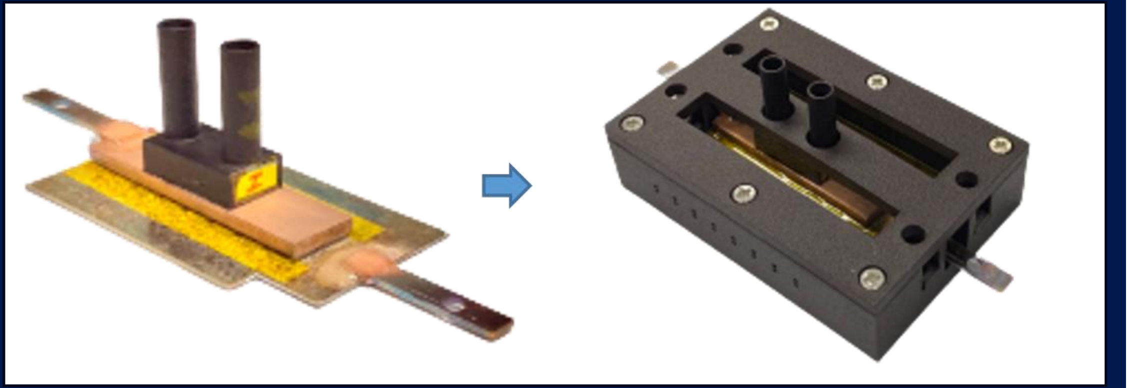


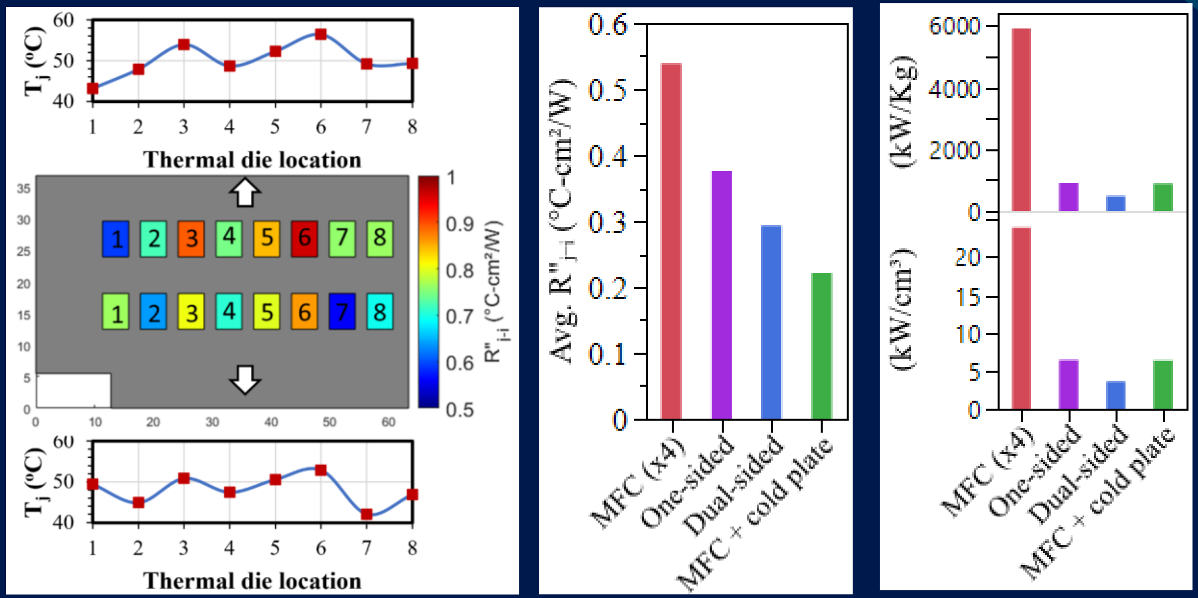


[12]: A. -C. Iradukunda et al., "Toward Direct Cooling In High Voltage Power Electronics: Dielectric Fluid Microchannel Embedded Source Bussing Terminal," in IEEE Transactions on Components, Packaging and Manufacturing Technology, doi: 10.1109/TCPMT.2024.3369554.

Performance Comparison External vs Integrated

- Flow capped at 1.255 LPM to stay under 11psi (75kPa).
- Poor die contact resulted in sporadic temperatures across the cooler.
- High thermal resistance result but improves with underside cold plate addition.
- Comparable performance to external cooler implementation.





[12]: A. -C. Iradukunda et al., "Toward Direct Cooling In High Voltage Power Electronics: Dielectric Fluid Microchannel Embedded Source Bussing Terminal," in IEEE Transactions on Components, Packaging and Manufacturing Technology, doi: 10.1109/TCPMT.2024.3369554.

Integrated Cooling Case Study

3.3kV, 200A power module

3.3 kV Low-Inductance Full SiC Power Module [1]

- UAPG develop 3.3 kV, 200A (SiC) half-bridge power module with
  - Compact formfactor (249.6 cm^3)
  - Symmetrical layout
  - Integrated capacitors and gate resistors
- Performance at least on par with commercial counterparts.

Package Characteristics	Value
Dimensions	104 x 100 x 24 mm
Module inductance (Q3D estimation)	6.9nH
Junction-to-case thermal resistance (per MOSFET, ANSYS estimation)	0.15°C/W
Integrated gate resistance	0.25 Ω

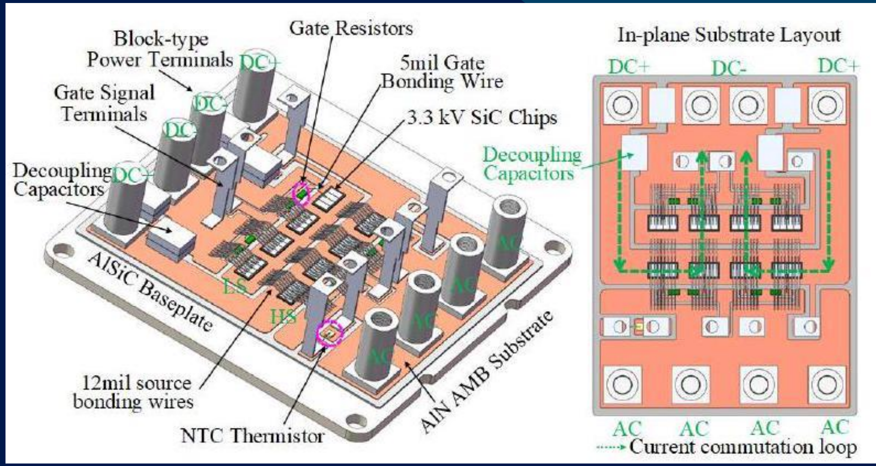


Fig. 1: Module Architecture.

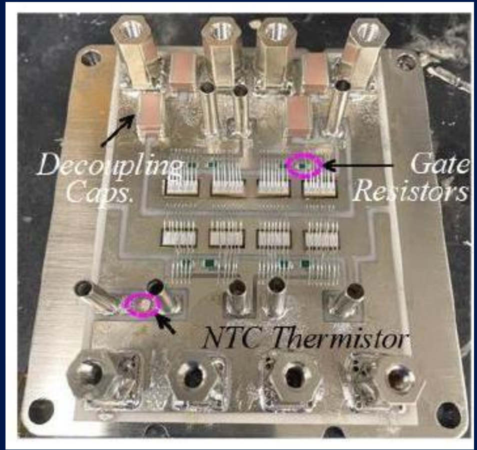


Fig. 2: Module internal layout

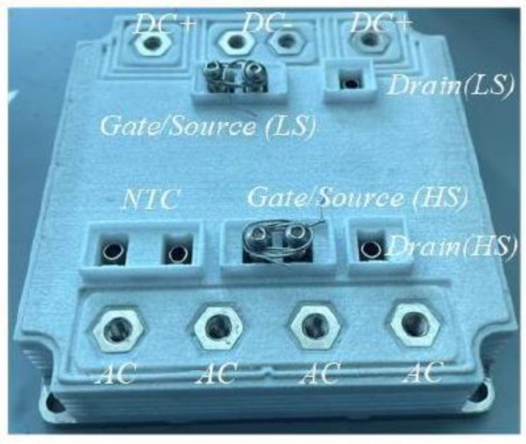
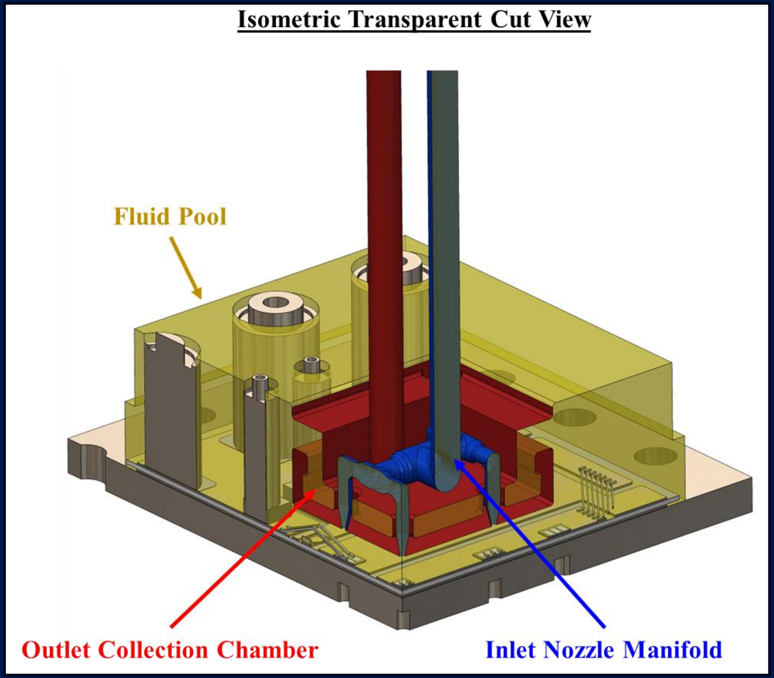


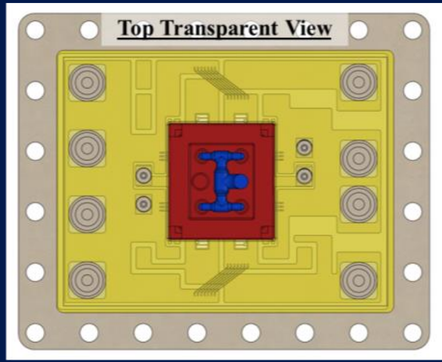
Fig. 3: Module appearance

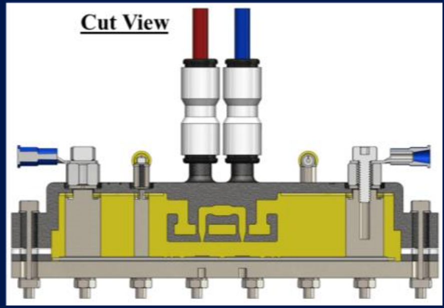
[1] Y. Chen et al., "3.3 kV Low-Inductance Full SiC Power Module," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 2634-2640, doi: 10.1109/APEC43580.2023.10131290.

Jet impingement Modification Details [11]

- UAPG modified the 3.3 kV, 200A (SiC) design with jet impingement integrated cooling
  - Water-tight baseplate/housing redesign
  - Used 1.2 kV power die (availability)
  - HFE 7500 dielectric fluid (19 kV/mm & K = 5.8)







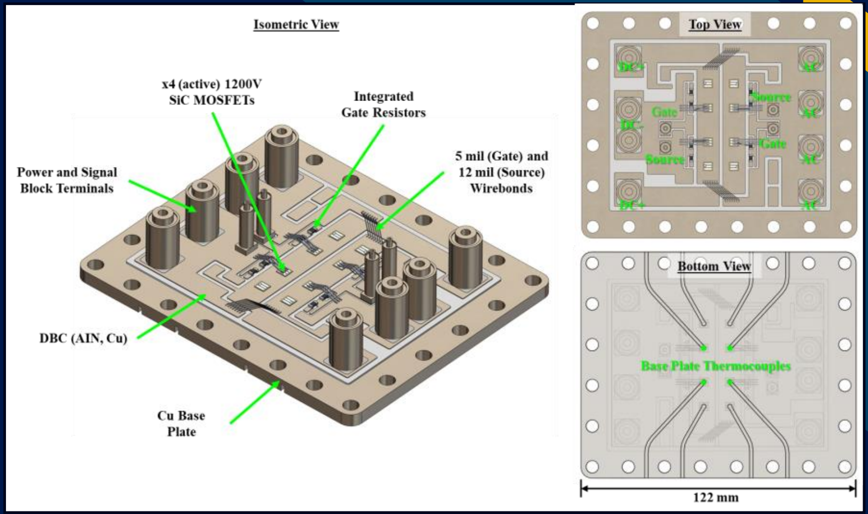


Fig. 1: Modified module Architecture.

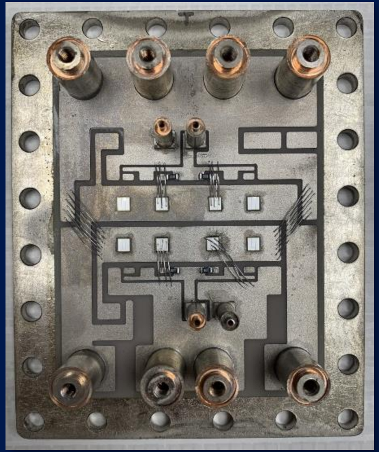


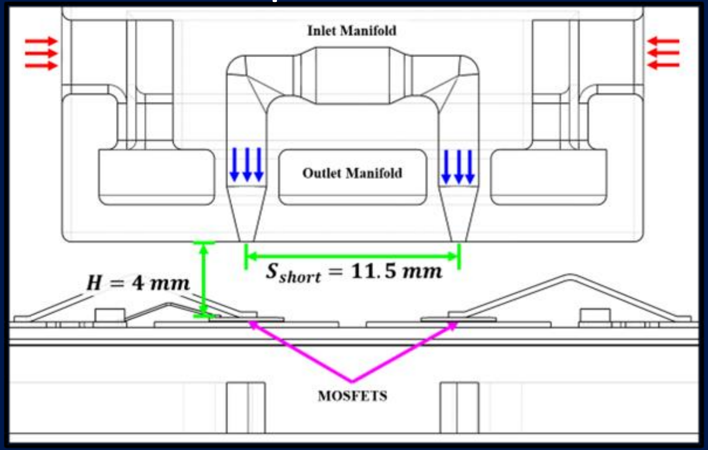
Fig. 2: Modified internal layout

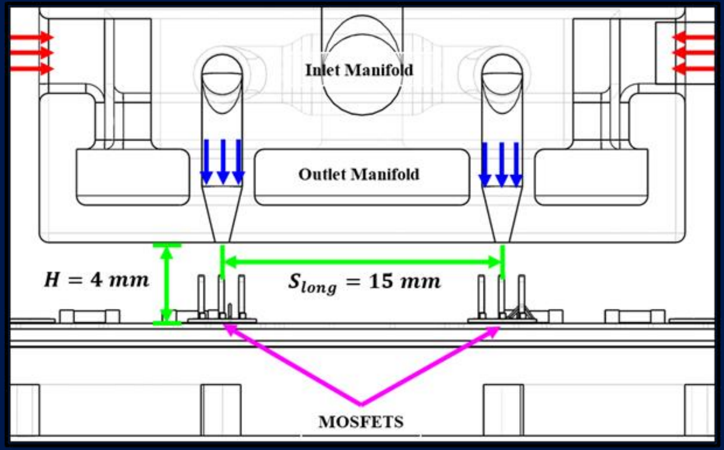
Fig. 3: Module appearance

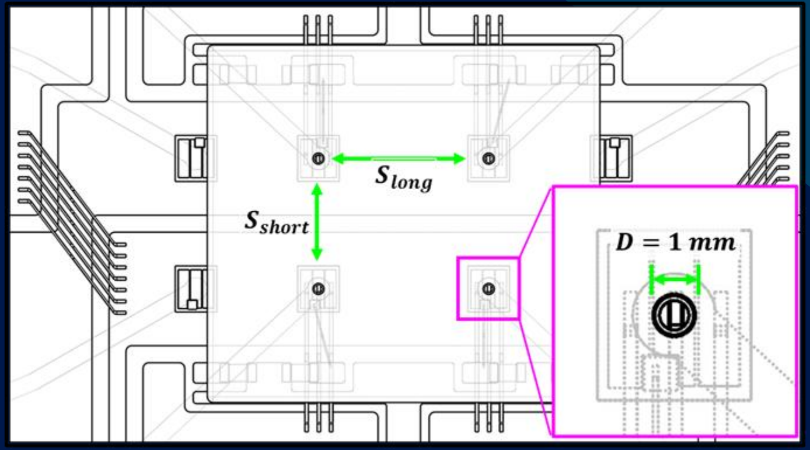
[11]: R. Whitt, D. Huitink, "Performance Metrics for Optimal Direct Jet Impingement Cooling w/ Dielectric Fluid", unpublished.

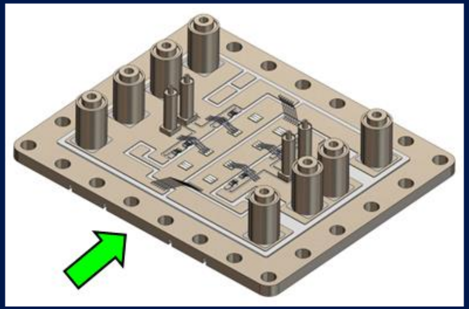
Jet impingement Design Considerations [11]

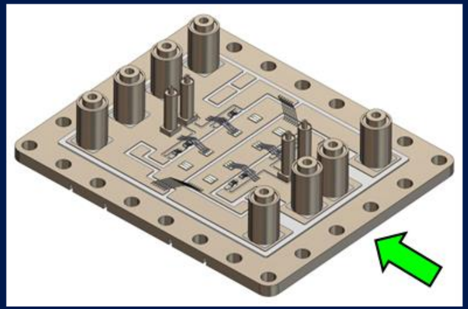
- Jet height chosen such that the ratio of jet-to-jet spacing/jet diameter (s/D) falls within optimal ranges based on literature review
  - Rule of thumb: no jet interaction when s/D > 8
  - Optimum: s/D = 12 when H/D = 4

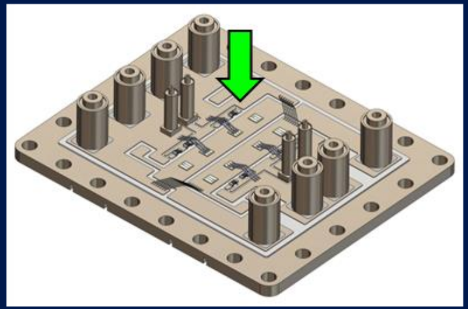










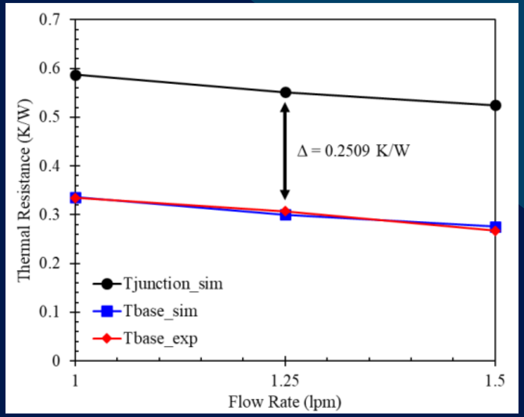


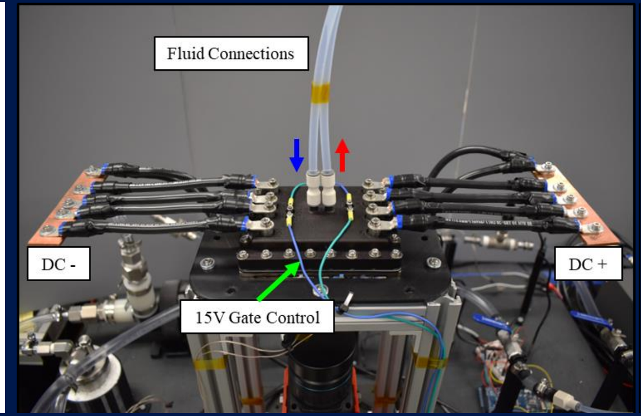
[11]: R. Whitt, D. Huitink, "Performance Metrics for Optimal Direct Jet Impingement Cooling w/ Dielectric Fluid", unpublished.

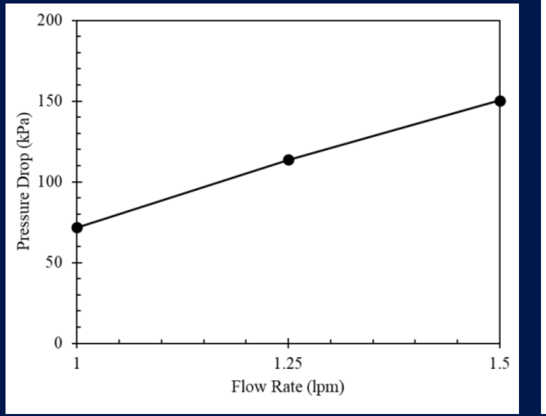
Jet Impingement Implementation Results [11]

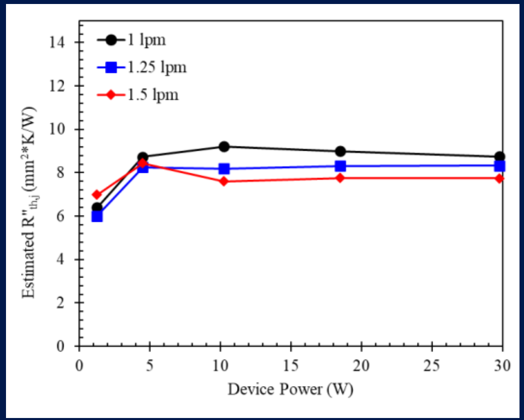
Module Test Results

- Flow rates ranged from 1 to 1.5 LPM
- Defects led to higher-than-expected pressure drops when compared to single jet prototype
- Thermal resistance estimated average of 0.08 cm^2K/W.









[11]: R. Whitt, D. Huitink, "Performance Metrics for Optimal Direct Jet Impingement Cooling w/ Dielectric Fluid", unpublished.

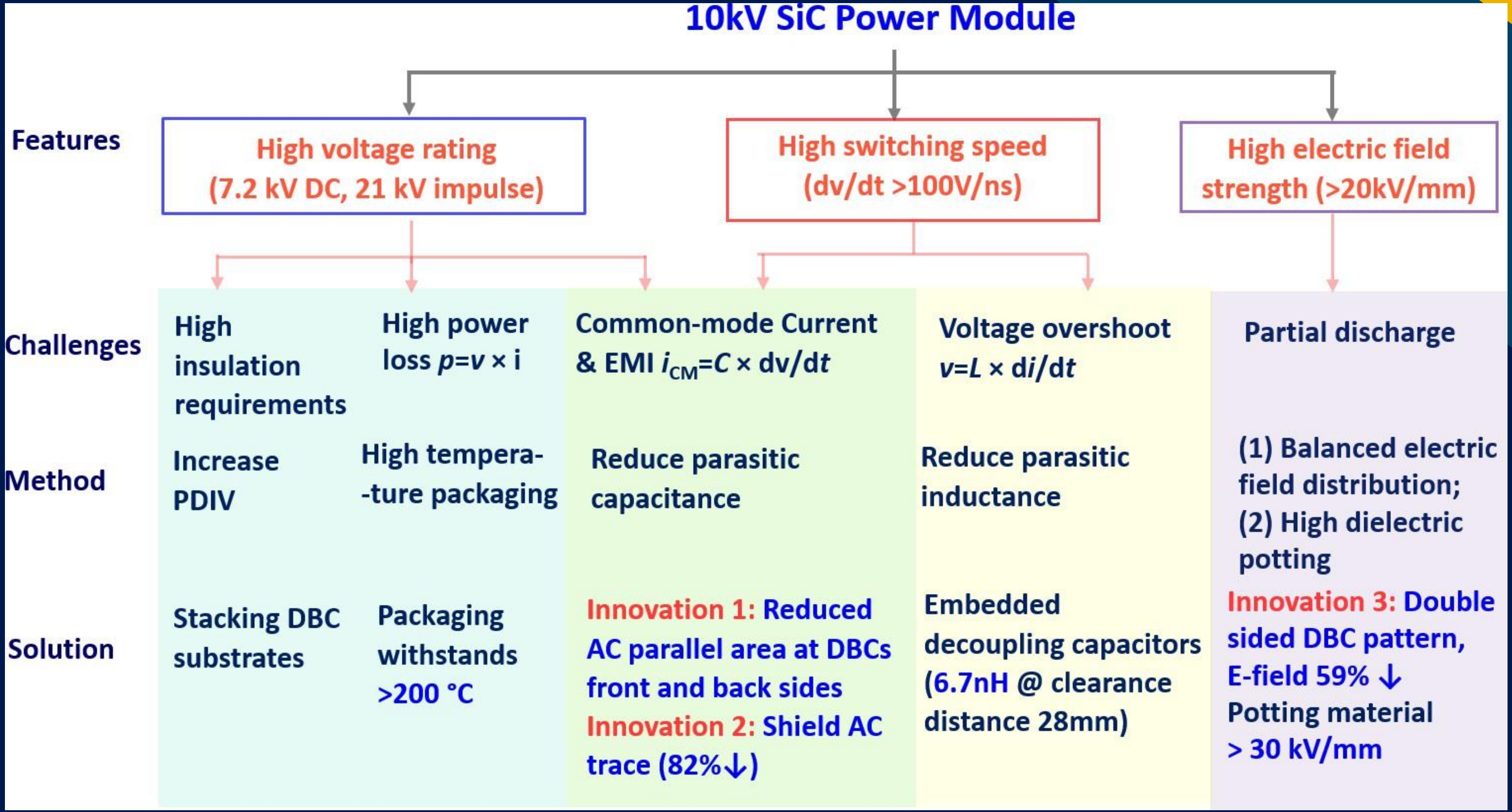
Custom 10kV Case Study

10kV, 60A power module

10 kV Power Module Design Challenges

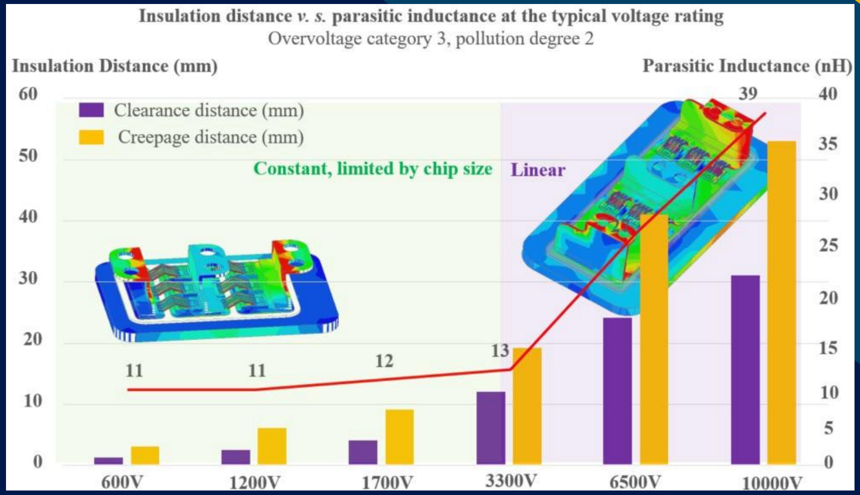
10kV power design has several challenges to overcome

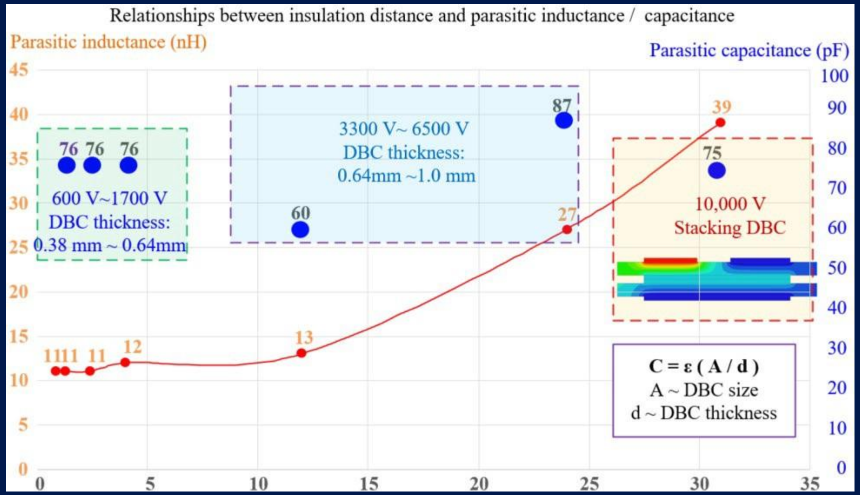
- High voltage rating
  1. Increased clearance requirements
  2. Much higher losses and parasitics expected
- High switching speed
  1. Resulting in noise and instability

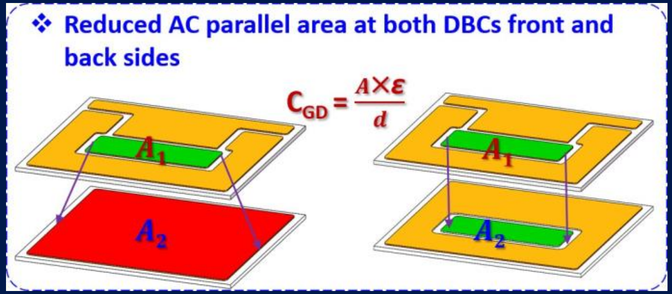


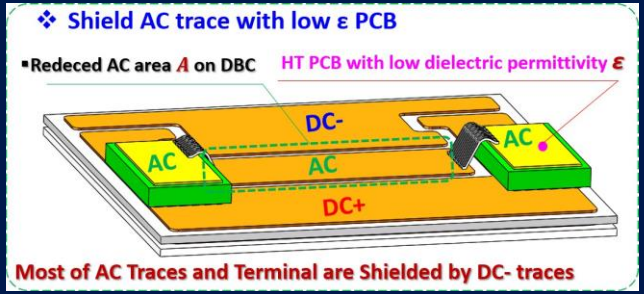
UAPG 10 kV SiC Power Module Design Criteria [2]

1. Insulation requirements vs. parasitics
   a. Voltage rating require increased clearances.
   b. Also require an increase in substrate insulation.
   c. Implemented solutions address all challenges focused on.



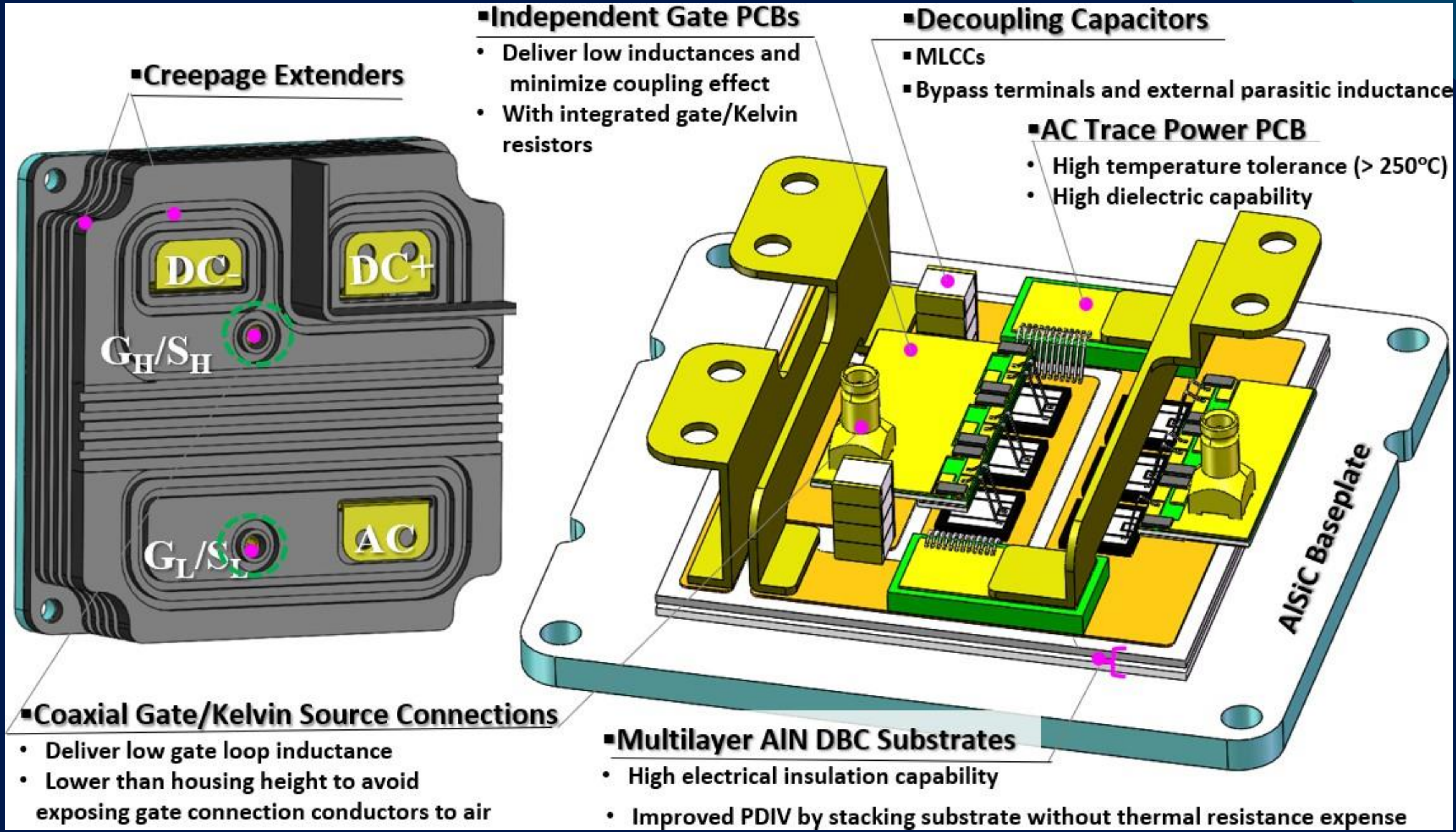






[2] X. Li et al., "A 10 kV SiC Power Module Stacked Substrate Design with Patterned Middle-layer for Partial Discharge Reduction," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 344-349, doi: 10.1109/APEC43580.2023.10131485.

UAPG 10 kV SiC Power Module Layout [2]



[2] X. Li et al., "A 10 kV SiC Power Module Stacked Substrate Design with Patterned Middle-layer for Partial Discharge Reduction," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 344-349, doi: 10.1109/APEC43580.2023.10131485.

10 kV SiC Power Module Comparison

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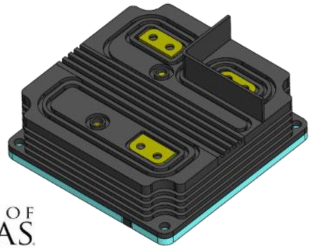
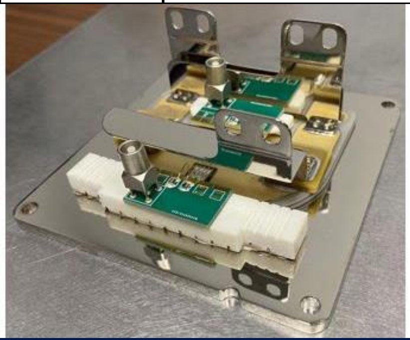
- **Experimental Validation**: Robustness confirmed via
  - Double-pulse test at 5 kV showing negligible ringing and voltage overshoot.
  - Partial discharge inception voltage (PDIV) verified at 16.8 kVrms.
- **Application & Impact**: Module terminal layout provides easier busbar implementation
- Parasitic impedances on par to commercial counterparts

	10 kV, 240 A CREE 	10kV, 60 A CPES 	10kV, 60A UNIVERSITY OF ARKANSAS 
L_{power}	16 nH	4.4 nH (10.3 nH w/o Cde)	5.1 nH (12.8 nH w/o Cde)
L_{gate}	10nH	4 nH	7.6 nH
C_{hs}	--	36 pF+ CM screen	27 pF
Terminal	DC+ and DC- are at two far ends respectively	DC+ and DC- are at two far ends respectively	DC+ and DC- at the same side (avoid complex busbar design)



Conclusion

The research conducted by the University of Arkansas represents a significant stride forward in the domain of custom, high-density power modules for electric vehicle and other high-voltage applications. By innovatively addressing the thermal management challenges inherent in power electronics, the team has not only enhanced the performance and efficiency of these systems but also paved the way for future advancements. The application of direct jet impingement cooling with dielectric fluids and the novel integration of microchannels within power module terminals exemplify the potential of thermal integration technologies to revolutionize power module design.

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